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# Forage Yield Estimation with a Process-Based Simulation Model

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Additional information is available at the end of the chapter

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## Abstract

A process-based simulation model of natural grasslands and improved pastures can be used to compare mean productivity and stability of forage productivity across years, agroecological regions, and management approaches. Model simulations can help farmers develop management practices to optimize livestock stocking rates and nutrient management for native and improved grasses on different soils with varying rainfall amounts. Likewise, forages are adapted to a wide variety of soils, rainfall zones, and latitudes. The objective of this chapter is to describe the Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) model that simulates a wide variety of environmental and management impacts on forage production, soil health, and conservation concerns, including nutrient and sediment losses. We describe the various processes simulated in the model and input data requirements. We also describe how to derive plant parameters for various forage plant species. The model has been applied to simulate forage yields across years and diverse environments in the U.S. and tested using published forage yield data from Natural Resources Conservation Service, United States Dept. of Agric. Many common native and introduced grasses or grass mixtures in the U.S. have been successfully simulated. We also describe and discuss knowledge gaps for the model that future research should address to improve this and similar simulation models.

**Keywords:** simulation modeling, native grasses, improved grasses, environmental quality simulation, forage management

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## 1. Introduction

A process-based simulation model of natural grasslands and improved pastures offers managers a science-based decision tool with many possible applications. Such a model can be used to

compare mean value of and stability of forage productivity across years, agroecological regions, and management approaches. Model simulations can help farmers develop practices to best manage livestock and to most effectively fertilize pastures for native and improved grasses on different soils with varying rainfall amounts. Likewise, how forage productivity responds to different grazing management can be simulated. The ideal model for these applications would have sufficient detail to simulate several plant species, soils, and climatic conditions without excessive input requirements. The model should be able to simulate forage legumes, improved grasses, and common native grasses, as sole crops or mixtures. The required plant parameters should be readily derived from published studies in conjunction with measurements that can be obtained without an inordinate amount of time and effort given to field experiments. This model will have process-based components to simulate leaf area growth, biomass production, and nutrient uptake. In addition, the soils and weather data needed should be readily available, and there should be data sets with sufficient detail for validating forage production simulations. Historically, there has been a diversity of process-based models developed to simulate dynamics of grass growth and dry matter yield for different species. Some examples of process-based models are GRASIM [1, 2], Simulation of Production and Utilization on Rangelands (SPUR) model [3–5], the Ecosystem Level Model (ELM) [6], and DAFOSYM [7].

GRASIM is a grazing simulation model designed to simulate intensive rotational grazing management linked to components (e.g., carbon, nitrogen, and water budgets) of the pasture system. This model predicts daily growth rate, biomass accumulation, protein and fiber content, and water and nutrient levels [1]. Simulation of Production and Utilization of Rangelands (SPUR) is a mechanistic process model designed to simulate growth initiation, germination, carbon assimilation, translocation between roots and shoots, N mineralization, and nitrogen uptake [8, 9]. SPUR has been modified and incorporated into the Integrated Farm System Model, IFSM, to simulate the growth and competition of multiple plant species in pastures [10]. The Dairy Forage System Model, DAFOSYM, is a simulation model of the dairy forage system. This model simulates plant growth of lucerne (*Medicago sativa*), maize (*Zea mays* L.), small grains, and soybean (*Glycine max*) using historical weather data. DAFOSYM evaluates the forage qualities and accumulation of dry matter based on daily weather and soil moisture.

### 1.1. Constraints on forage production

Forages are adapted to a wide variety of soils, rainfall zones, and latitudes. The environment imposes different constraints on forage production, including but not limited to the following:

1. Varying durations of growing seasons due to temperature and light availability. These are obviously highly dependent on latitude.
2. Available water, including low annual rainfall, variable intra-annual rainfall patterns, and flooding events.
3. Soil attributes:
  - a. pH
  - b. Soil depth (rooting zone and hydrological dynamics)

- c. Soil water storage capacity as impacted by soil texture
- d. Slope and rock fragment that impact infiltration/runoff rates
- e. Aeration differences with some soils having prolonged flooding
- f. Soil nutrient variability, due to either inherent soil fertility or applied nutrients that include organic and inorganic fertilizers

The complexity of these factors and their interactions make forage management a challenge. Animal stocking rates, haying frequency, and optimum fertilizer applications add to the complexity. A producer must take all of these factors into account, plus personal experiences and expert opinion to manage forage lands. However, a process-based simulation model could provide a more science-based approach to management decision making. By systematically simulating forage growth with different soils, weather, plant species, and management systems, such a model will be a valuable tool. In addition, built-in water and nutrient balances in the model allow users to derive guidelines that producers can apply to better adjust management practices among years with high, low, or normal rainfall patterns. Likewise, impacts of various management scenarios on soil erosion, soil organic matter buildup or depletion, and water quality can be evaluated.

The ALMANAC model is adaptable to any species of forage in any geographic location, provided adequate input data are available to inform the model simulation. It can be used to simulate a diversity of forage species as well as woody species, crops, and interspecies competition. The model can simulate plant growth using independently derived plant parameters, with no recalibration among sites. It includes components for the water balance, the nutrient balance, and interception of solar radiation by monocultures or competing plant species. Daily values for weather variables, including temperature and rainfall, are required. Soil inputs are readily available from published USDA-NRCS soil surveys. When fully calibrated, ALMANAC has been shown to reasonably simulate native grass productivity on diverse sites in the U.S. as well as improved grass species at several U.S. sites as discussed below. The objective of this chapter is to describe the Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) model [11], a process-based model capable of considering a broad variety of environmental and management impacts on forage production, soil health, and conservation concerns, including nutrient and sediment losses.

This chapter consists of five sections:

**ALMANAC model simulated processes:** The basic processes ALMANAC simulates are described, including processes specific to forage simulation, to include:

- a. Cessation of forage plant development due to intense drought stress (Growing degree day accumulation stops temporarily)
- b. Midseason dormancy in cool season forages when the daylength gets sufficiently long. This model functionality enables simulation of the bimodal growth pattern observed in such grasses (e.g., tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort)).

- c. Plant competition for water and nutrients, including woody species competing with herbaceous forages

**Soils and weather data:** The available and required soils and weather data are described.

**Deriving plant parameters for a forage species and accommodating ecotypes:** The steps for deriving plant parameters for various forage species and ecotypes are outlined.

**Model testing against independent data:** Soft calibration of the model via comparison of outputs to independent data to ensure the model is working reasonably well is described and discussed.

**Knowledge gaps and areas for future improvement as a guide for additional research:** Finally, the knowledge gaps and potential areas for improvement are outlined, as a guide for potential additional research.

## 2. ALMANAC model simulated processes

Phenological development defines the duration of various plant growth stages and determines the length of the forage growing season. The ALMANAC model simulates phenological development with a growing degree day (GDD) system, species-specific base temperature, and optimum growing temperature. The sum of GDD calculates the duration of the growing season. Anthesis date is predicted with a defined fraction of the total GDD sum to physiological maturity. Daylength and drought affect simulated forage phenology as described below.

Leaf area growth is simulated on a whole canopy basis, with potential leaf area index (LAI) defined for each species/ecotype/variety. These are hereafter referred to as just “species.” The climate and soils at different sites often dictate the plant density of forages, thereby affecting the potential LAI.

The development of LAI over the growing season is simulated with a 0.0 to 1.0 “S” curve defined for each species. Thus, LAI is simulated as a function of the ratio (current summed GDD)/(GDD to maturity). This ratio typically approaches 1.0 as the plants approach anthesis and transition from forage production to reproduction. The “S” curve thus defines the potential leaf area growth over the growing season.

Daily dry matter accumulation is simulated using a radiation use efficiency (RUE) approach. The potential dry matter produced each day is a function of the amount of photosynthetically active radiation (PAR) intercepted by the leaf canopy on that day. The RUE is a species-specific value (g of dry matter per MJ of intercepted PAR).

Partitioning among plant parts is also on a whole canopy basis. The root and shoot partitioning is defined by two parameters. Plants initially partition a greater fraction of the total dry matter production into the roots. This fraction decreases as plants approach anthesis. Stresses, especially drought, reduce the above-ground dry matter production more than the root dry matter production. This causes drought stress to change the simulated root:shoot ratio.



Partitioning of plant energies to the seed is simulated with a harvest index (HI) approach. The fraction of the total plant weight in the seed at maturity relative to the total plant weight is the species-specific HI parameter. While very small for most forage species due to their relatively small fruits and seeds, the partitioning into the seed begins after anthesis and is complete by physiological maturity.

Environmental stresses decrease leaf area expansion and dry matter accumulation. As described below, the model simulates the impacts of a variety of stresses each day. The most severe stress each day constrains leaf area growth and dry matter accumulation. Leaf area growth is more sensitive, especially to drought, than is dry matter growth.

Drought stress is simulated using the potential evapotranspiration (PET), calculated as a function of daily weather variables. The available soil water in the current rooting zone is calculated each day based on rainfall, soil infiltration, and soil water-holding capacity. If available soil water in the current rooting zone is insufficient to meet the plant's demand (based on PET and leaf area index), the model simulates a drought stress response in the plant through decreased leaf expansion rates and reduced dry matter accumulation rates.

Nutrient stresses, particularly nitrogen (N) and phosphorus (P) stresses, reduce plant growth. These nutrient stresses are simulated with a supply and demand approach. Plant N and P nutrient uptake is simulated with three input parameters that define how nutrient demand changes during the growing season. For each plant species, the optimum amount of available N and P is defined for each species early in plant development, near anthesis, and at physiological maturity. These three values are used to calculate the potential nutrient uptake from the soil each day. If the N and P in the current rooting zone are insufficient to meet demand (calculated from the optimum percentage of the nutrient and the potential daily plant dry matter growth), the model simulates nutrient stress by decreasing the species' dry matter accumulation rate and leaf expansion rate.

Temperature stress can also reduce plant growth in the model. Each plant species has a defined base temperature and an optimum temperature. When daily temperature is below the base temperature, cold temperature stress occurs. When temperatures are above the optimum, high temperature stress occurs.

Aeration stress is also simulated. When soils are saturated with water, aeration stress occurs in the model. Plants have variable sensitivity to aeration stress, as defined by the species-specific value of critical aeration factor (CAF). Plants such as eastern gamagrass (*Tripsacum dactyloides* L.) and rice (*Oryza sativa*) are less sensitive to poor aeration conditions, such as flooding, while upland grasses are more sensitive.

There are components in the model developed specifically for forage simulation. Forage development is not only dependent on GDD accumulation, but also on daylength and stresses. In order to accommodate growth dynamics typical of arid ecosystems where forage species are grown without irrigation, the model was modified so that sufficient drought stress stops GDD accumulation in the model. This is in addition to the direct effects on leaf area growth and dry matter increases as discussed above. As we began simulating plant growth in more arid environments, we had to introduce the ability to halt plant development when drought stress

became sufficiently intense. Thus, we introduced a function that stops GDD accumulation (thus stopping phenological development), when the zero-to-one drought stress factor is less than 0.4.

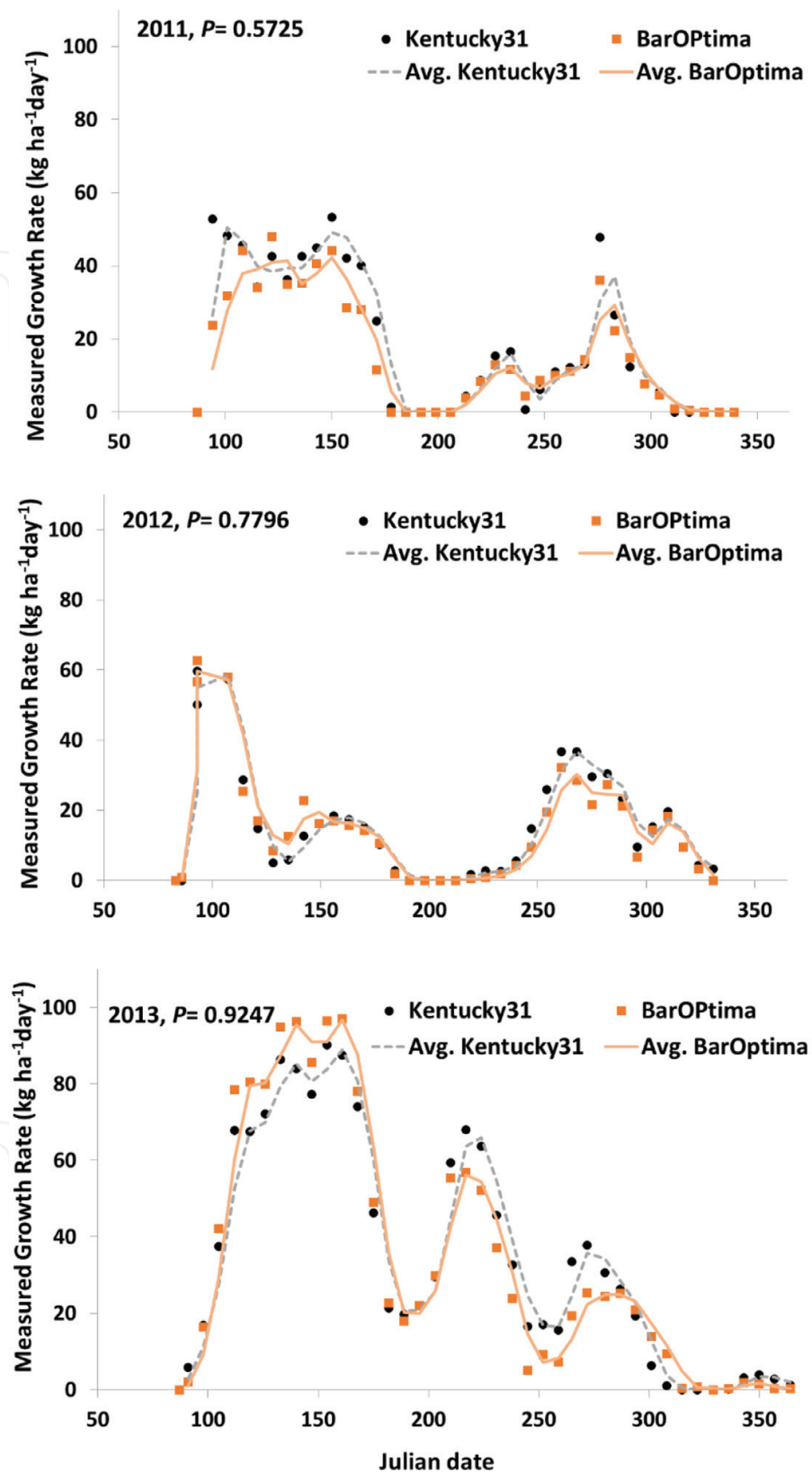
The ALMANAC model is capable of simulating growth patterns exhibited by different types of forages. Cool season forages such as tall fescue often exhibit two intervals of active growth, with a slowdown during the hottest days of the year. Actual growth patterns of tall fescue in southwestern Missouri over 3 years [12, 13] are shown in **Figure 1**. We incorporated a mid-season dormancy function to simulate this. Thus as daylength gets sufficiently long plant growth slows and stops. The model now simulates this rapid growth in the spring, slowing and stoppage of growth near mid-season, and subsequent late summer and early fall growth. The forage-simulation functionality of ALMANAC stops plant growth and development when the maximum photoperiod of the year is reached and restarts growth when the photoperiod subsequently gets sufficiently short to trigger reinitiation of growth. This model functionality was developed based on observed tall fescue growth curves measured in Missouri [12–14].

Subsequently, we tested the model's simulation of tall fescue yields with USDA-NRCS reported yields for a number of sites and soils across the main regions of tall fescue pastures in the U.S. [14]. We used long-term measured weather and the appropriate soil parameters for these simulations. We compared the simulated yields to the reported yields for the low-yielding sites, the high-yielding sites, and for all the sites pooled (**Figure 2**). The model with this function did an excellent job of simulating tall fescue yields on sites with differing reported yields across the main areas of tall fescue production in the U.S.

Additionally, ALMANAC simulations accommodate winter dormancy, typically observed in forage species when daylength gets sufficiently short in the fall. This capacity has been well tested on winter wheat [15], which is planted in the fall, goes dormant during the winter, then restarts growth in the spring. A parameter (DORMNT) defines this interval by defining the hours of photoperiod near the minimum for the latitude when plants are dormant. If the value is 1.0, during the winter when the photoperiod is within 1.0 hour of the minimum for the latitude, plants remain dormant.

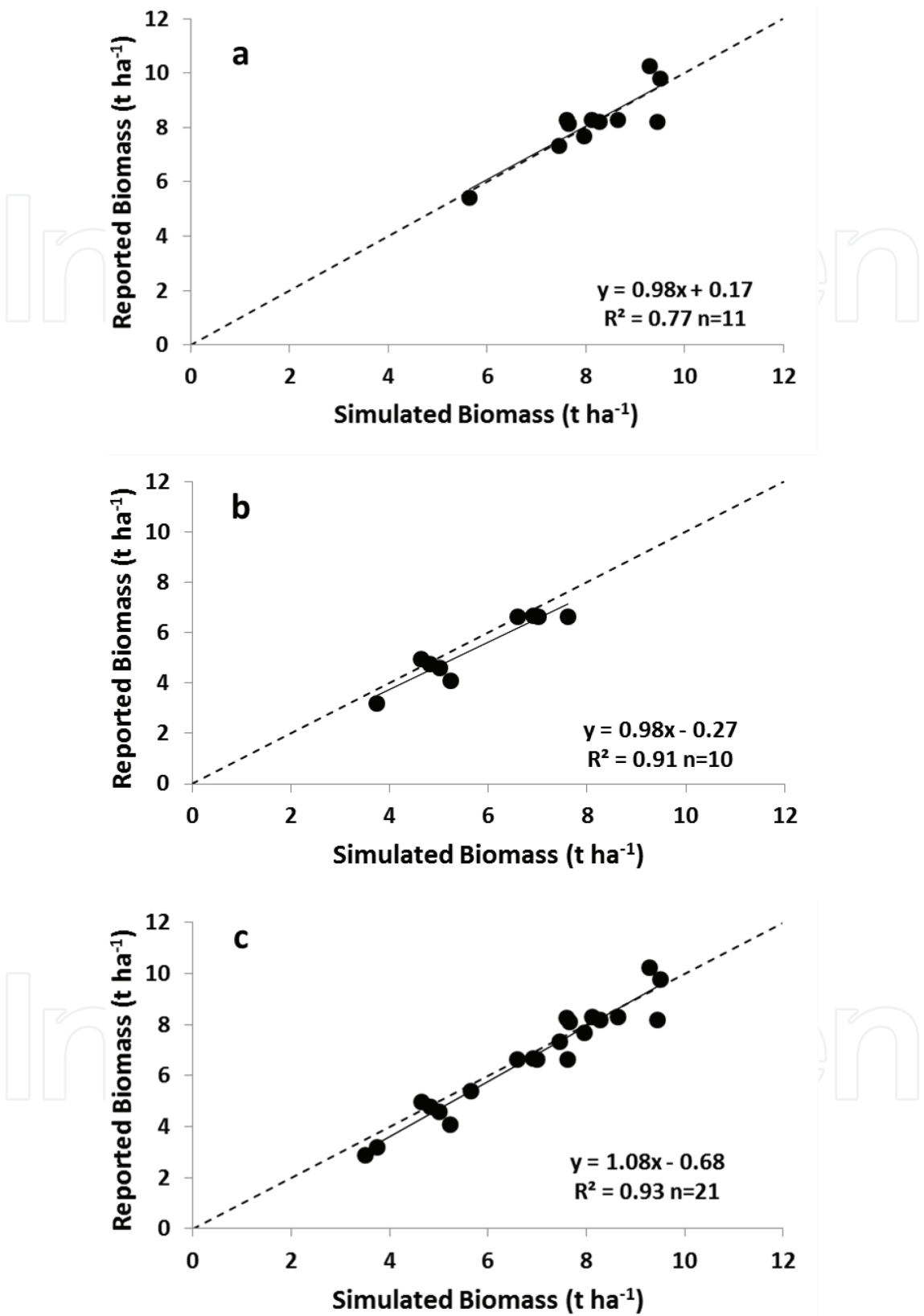
Simulation of grazing and hay harvest is especially important when simulating forages. The model resets development (summed GDD, LAI, and height) when the simulation includes a grazing event or the forage is cut for hay. The model simulates a daily value for plant height from the fraction of GDD relative to the physiological maturity value and a species-specific plant height parameter (CHT). When forages are grazed or cut for hay, this height is reduced. If grazing or hay cutting reduces the plant height by 90%, the summed GDD for that day is reduced by 90% and the leaf area and above-ground dry matter is reduced by 90%. The plants then begin regrowth the following day.

Forage plant communities often have mixtures of species, due to the diversity typical of a native prairie, due to intercropping of legumes and grasses to better accommodate nutrient demands, or due to invasion of the forage site by undesirable herbaceous or woody plants. The ALMANAC model is capable of simulating both nitrogen fixation benefits to non-nitrogen-fixing species and competition between plant species. The ALMANAC model was initially



**Figure 1.** Measured plant growth rates ( $\text{kg ha}^{-1} \text{ day}^{-1}$ ) for “Kentucky 31” and “Bar Optima” tall fescue in 2011, 2012, and 2013 at Mt. Vernon, MO. The Wilcoxon Rank Sum test was performed to compare “Bar Optima” and “Kentucky 31” growth rates within each year at  $\alpha = 0.05$ . Source: adapted from Kiniry et al. [14].





**Figure 2.** Reported (USDA-NRCS) and simulated tall fescue yields for (a) high-yielding soils, (b) low-yielding soils, and (c) high- and low-yielding soils at diverse sites in the U.S. Source: adapted from Kiniry et al. [14].

developed to simulate competition between crops and weeds and has been applied to communities of plants such as native range sites and woody plants competing with forages. Aspects of competition simulated in ALMANAC include competition for light, water, and nutrients.

The fraction of incoming solar radiation intercepted by the leaf canopy (FI) is:

$$FI = 1.0 - \exp(-k \cdot LAI) \quad (1)$$

The light extinction coefficient ( $k$ ) for Beer's law [16] is calculated for each harvest date as:

$$k = [\log_n (1 / FIPAR)] / LAI \quad (2)$$

where  $\log_n$  = natural log of the number, and FIPAR = fraction of IPAR.

The value of  $k$  has been determined for a number of forages in the U.S. [17–20]. Realistic simulation of LAI is critical for these equations describing light interception. This is true for both the increase of LAI during active growth and the decline as leaves senesce. The model uses an S-curve to simulate the accumulation of leaf area increase as a function of GDD.

Similarly, as described above, biomass growth is simulated with a radiation use efficiency (RUE) approach [17, 21]. The RUE is calculated as the rate of increase in dry matter (g per m<sup>2</sup> ground area) per unit of intercepted photosynthetically active radiation (IPAR) (MJ per m<sup>2</sup> ground area). Regressions are fit with the treatment means of plant dry weight and summed IPAR for each sampling point. The RUE is the slope of the regression for this plant weight (g m<sup>-2</sup>) as a function of the summed IPAR (MJ m<sup>-2</sup>).

This regression is ideally based on multiple harvest dates during the active growth period of the forage. Occasionally, when only two harvest dates are usable, RUE is calculated from differences. Only data from dates showing increases in dry matter (actively growing) are included. This constrains RUE values to periods of active growth. Data from sites experiencing drought stress are avoided. Values for FIPAR are calculated on a daily basis, with values for dates between measurement dates calculated by linear interpolation.

Simulated light competition uses functions of [22], whereby the light interception of each plant species in the mixture is computed with the following formula:  $LAI \cdot k$  ( $k$  being the light extinction coefficient). These products ( $LAI \cdot k$ ) of each species are summed and the sum used in Beer's law to compute the fraction of light interception by the whole plant community. This fraction of light intercepted for the whole plant community is then divided among the competing species by weighted fractions. The weights account for differences in species heights and  $LAI \cdot k$  of the species. Thus, taller species and those with higher LAI values and higher  $k$  values intercept a greater fraction of the total light intercepted by the plant community.

Water and nutrient competition are simulated with a balance sheet approach. Once intercepted light for each plant species is computed as described above, the potential daily biomass growth is calculated for each species with the total daily incident solar radiation, assuming 45% of that is PAR [23, 24]. The RUE for the species multiplied by the intercepted PAR is the potential biomass growth on any given day. Using the optimum nutrient concentrations for N and P at

the current growth stage, the demands for N and P are calculated. If insufficient N and/or P is present in the current rooting zone, the model reduces simulated growth rates to account for N and/or P stress. This simulation of the balance of nutrients is done for each species within a mixture. The model accounts for variability in root scavenging capacities between species only through differences in the current rooting depth of each species. Potential rooting depths of various plant species are derived from measurements reported in the literature for forages grown on soils with no restrictive soil layers (such as in [17]).

Likewise, potential plant transpiration is calculated from the potential evapotranspiration and the total community LAI. If soil water in the current rooting zone is insufficient to meet the species' demand, simulated drought stress occurs and limits growth. This occurs for all plant species present. However, it should be noted that a deeper rooted plant species may have access to soil water (and nutrients) not available to any competing shallower rooted species; ALMANAC accommodates different rooting depths of species. The deeper rooted plant species may have adequate soil water and nutrients to avoid drought and nutrient stresses when a shallower rooted species is stressed. The ALMANAC model does not currently simulate hydraulic lift dynamics and the potential impacts of lift on water and nutrient redistribution.

### 3. Soils and weather data

The soils and weather data described below are specific to the U.S. These are described in more detail, including how to download them at: <https://www.ars.usda.gov/plains-area/temple-tx/grassland-soil-and-water-research-laboratory/docs/193226/>. The soil and weather data for the country of Mexico have also been developed and formatted for ALMANAC model simulations (<https://www.ars.usda.gov/plains-area/temple-tx/grassland-soil-and-water-research-laboratory/docs/almanacmex/>). As the model is applied outside of these two countries, the input data for soils and weather (as well as plant species growth curves) can be developed through cooperation with the senior author of this project.

The general philosophy of input data development is to make this model and other USDA-ARS models (including EPIC [25], APEX [26, 27], and SWAT [28–30]) readily and easily applied. Input data are constrained by what is readily available and easily accessible. This means the daily weather inputs required consist of maximum and minimum temperature, rainfall amounts (and snowfall amounts), and solar radiation. When unavailable for a given location, solar radiation can be derived; wind speed and relative humidity can be used to approximate solar radiation. Weather data from the U.S. National Oceanic and Atmospheric Administration (NOAA) websites are readily downloaded for any state in the U.S. via the steps outlined in the model documentation (see website link above).

Similarly, required soil data are available through USDA-NRCS (<https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/>), which has the most extensive and verified, publicly-available soil database for the U.S. The soil data are readily downloaded for any state in the U.S., with the steps outlined in the ALMANAC model documentation. The most critical components of the soil data inputs are the depth, texture, and amount of rocks by soil layer.

For each soil layer, the values for saturation, drained upper limit, and lower limit are used by the model. Soil organic matter is another input that impacts plant-available water and soil carbon balances in the model. The amount of runoff from rainfall events is calculated with the traditional runoff curve number system. The runoff is simulated with the slope and type of ground cover.

## 4. Deriving plant parameters for a forage species and accommodating ecotypes

### 4.1. Field plant species measurements

The group of readily derived plant parameters includes the potential leaf area index (LAI), the development curve for LAI over the growing season, the light extinction coefficient for Beer's law ( $k$ ), the radiation use efficiency (RUE), the duration of the season in degree days, the harvest index for seeds (HI), and the N and P concentrations for each species over the growing season. All of these should be derived from measurements of a plant stand grown in a relatively stress-free environment to establish potential values for these for each forage species and ecotype. This means that ideally species being measured in field conditions should not have stresses due to drought or nutrient deficiency.

Details on taking field measurements for deriving plant parameters are outlined in detail under the headings: "Gathering Field Data, How to Use Ceptometer: AccuPAR LP-80 Basics Standard" [31] and "Taking measurements for ALMANAC: Sampling Protocol Standard with Photos" (<https://www.ars.usda.gov/plains-area/temple-tx/grassland-soil-and-water-research-laboratory/docs/193226/>) (Figure 3).

Field-derived values for the critical species-specific parameters have been described previously [17–21]. The model simulates light interception by the leaf canopy with Beer's law [16]



**Figure 3.** Intercepted photosynthetically active radiation (IPAR) measurements using an AccuPAR LP-80 Ceptometer at Bishop, California, and Bryan, Texas.



and the LAI. Larger values of the extinction coefficient have more light intercepted at a given LAI.

Measurement of light interception by the plant canopy is described at the website: <https://www.ars.usda.gov/plains-area/temple-tx/grassland-soil-and-water-research-laboratory/docs/193226/>. To derive leaf area, biomass, and the extinction coefficient for Beer's law, LAI measurements are derived every 2 weeks during the active growing season via light measurements taken above and below the canopy between 10 a.m. and 2 p.m. on a clear day. The Decagon ceptometer (or something similar) is used to measure light as photosynthetically active radiation, since those are the wavelengths critical for photosynthesis. A random sample area for the area of interest is chosen where the forage is growing. The stand in the area for taking light measurements should not be trampled. Areas adjacent to where previous samples were taken should be avoided and should be ungrazed. A quadrat 0.5 m wide by the length of our light bar (0.8 m) is reasonable for the sampling area.

If there are any non-targeted plants in or overshadowing our quadrat, they should be removed, or the quadrat should be relocated. Only canopy cover from targeted species should be measured. The time of day, average phenology, and the average plant height in centimeters should be recorded. Light interception readings using the ceptometer are taken as:

- a. Select an area under direct sunlight near our plots, and level the external sensor on the tripod. (*Note: Whenever moving the tripod, level the sensor and calibrate again.*)
- b. Calibrate the light bar with the external sensor. Take at least 10 measurements with the light bar under direct sunlight. (*Note: Make sure measurements are taken facing the sun, thus avoiding shading the light bar or the external sensor.*) Record the shown average of all 10 measurements on the datasheet.
- c. When taking light measurements under the canopy using the ceptometer, take at least six evenly spaced measurements in each quadrat near ground level. Record the average. Always take care to avoid biasing the sample in favor of more plants or more bare ground.
- d. Finally, harvest plants, removing all plant material in the quadrat directly above the site where light was measured and place in labeled bag.

Repeat these steps at least three more times for a targeted plant species. For each set of measurements, make sure to measure plants on the same soil or ecological site. When returning to the general area for future measurements, select the same species to measure but not the exact same plant/plot area as previously measured.

Process plant material as soon as possible after sampling to avoid desiccation effects on leaf area.

- a. When weighing the entire sample from field, if the entire sample is greater than 100 g, take a representative subsample. This is between 10 and 30% of the entire sample but no less than 100 g. Weigh and record the subsample weight. Make sure to select a subsample with the same proportion of green leaves, dead material, stems, and reproductive structure as the entire sample.



- b. Use a belt-driven leaf area meter (or something similar) to measure leaf area of the subsample. Separate the subsample into dead material (anything completely brown), stems, leaves, and reproductive structures. Record the weight of the dead material, stems, and reproductive structures.
- c. Determine the area of each structure using the leaf area meter. Run the dead material, stems, leaves, and reproductive structures through separately and record the area of each. Place the entire sample into a paper bag. These samples are dried in a 66°C forced air oven for 3 days or until weight stabilizes. Then record the dry weight of the entire sample.
- d. Finally, grind dry sample to prepare for nutrient analysis.

## 5. Model testing against independent data

Following successful calibration of the ALMANAC model with field measured parameters, the model was applied to simulate forage yields across years and diverse environments in the U.S. For model testing, we used published forage yield data from Natural Resources Conservation Service, United States Dept. of Agric. 2017. Web Soil Survey. Available online: <http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx>.

Many common native and introduced grasses or grass mixtures in the U.S. have annual productivity values reported as USDA-NRCS ecological site productivity (for native forages) or NRCS crop productivity (for improved grasses) for many representative areas. As discussed below, once plant parameters for a particular forage are derived, they are tested on different soils in contrasting U.S. counties. The counties simulated are selected because they have soils with quantified annual biomass yields for the forage of interest (NRCS Web Soil Survey) (<http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>).

Total annual production of forages reported by NRCS are derived from end-of-season sampling on sites with closed canopy stands of the species of interest over 3 years or more. The NRCS procedure involves measuring dry matter biomass production above a 5-cm cutting height in at least 10 randomly selected plots at each field site. The specific soils for a location of interest can be downloaded as described above. Mean simulated forage yield over 10 years of real weather data can be compared to the reported annual production (from USDA-NRCS Web Soil Survey) for a site. The NRCS value of Animal Unit Month (AUM) is converted to  $\text{Mg ha}^{-1}$  (0% moisture) with a conversion factor assuming 700 lbs. (318 kg) of air-dried biomass (90% moisture) per AUM. Values for key plant parameters for the plant species of interest are derived from the field measurements described above.

### 5.1. Examples of testing ALMANAC's simulation of forage yields

We have several published examples of testing ALMANAC's simulation of forage yields. The first was for several Texas range sites with native warm-season grasses [32, 33]. Next, we simulated old world bluestems (*Bothriochloa* Kuntze, *Capillipedium* Stapf, and *Dichanthium*

Willemet) and buffelgrass (*Pennisetum ciliare* (L.) Link) in Oklahoma, Texas, and Mexico [18]. To evaluate the ability of the model to simulate introduced or improved grasses, we tested coastal bermudagrass (*Cynodon dactylon* (L.) Pers.) and bahiagrass (*Paspalum notatum* Flüggé var. *saurae* Parodi) at several sites in Texas [19]. Western grasses in low-rainfall sites in Montana were simulated using parameters derived for some common native grasses there [20]. The cool-season forage “tall fescue” was simulated at several sites in several states where this grass is commonly grown [14]. In addition, creosote bush (*Larrea tridentata* [DC.] Cov.) parameters were derived and model testing for its ability to describe competition of this woody species with forages in arid sites in western Texas [34].

Overall, the ALMANAC model predicted forage yields with reasonable accuracy, and hence when fully calibrated, the model can be used as an effective management tool to evaluate management practices that maximize forage yields, optimize inputs, and minimize negative environmental outcomes.

## 6. Knowledge gaps and areas for future improvement as a guide for additional research

The ALMANAC model uses the best plant growth modeling functions currently developed. Often, knowledge gaps force model developers to use placeholder functions with the hope that future research will enable development of improved, more realistic functions. Some areas for beneficial future research include nutrient and carbohydrate cycling, forage regrowth following haying, nutrient response functions, and legacy effects.

The simulated cycling of nutrients in the soil and between the roots to the shoots for perennials needs to be critically investigated for this model. As forages mature and leaves senesce during the fall and winter, often nutrients and carbohydrates are translocated back into the root system, to be used for regrowth the following spring. Grazing may also trigger plants to allocate more carbohydrate storage in roots to survive grazing pressures. Functions describing these processes need to be better developed and incorporated into the ALMANAC model in the future.

Likewise, the regrowth of forages following hay cutting or grazing within the growing season, needs to be more extensively tested. The functions currently in ALMANAC appear to function reasonably. However, as more extensive data are available for testing the model, improvements likely will be made.

The response of forages to applied nutrients often is highly dependent on what is already in the soil. This includes nutrients readily available and those coming from transformations within the soil during the growing season. Very often publications report a nutrient response of a forage without adequately describing initial soil conditions. If adequate nutrients are already present in the soil, the response of the forage to applied nutrients can be much dampened. Likewise, if the soil is initially very nutrient poor, the forage may show a large response to applied nutrients. An extensive testing of the model with data having good values for initial soil nutrients will be valuable.

Finally, legacy effects due to previous years' weather conditions and previous years' nutrient cycling need to be investigated. This has been studied with switchgrass [35], but needs more extensive studies with diverse representative forages.

## 7. Conclusions

In this chapter, we described the ALMANAC model, including the process simulated, how to derive plant parameters for additional forage species, and how to validate using measured field data. Because of its accurate simulation of plant production, the water balance, and the nutrient balance, the model is capable of simulating a wide variety of environmental and management impacts on forage production, soil health, and conservation concerns, including nutrient and sediment losses. The model will be a useful and valuable tool for forage management in pastures and rangelands in a wide range of conditions.

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## Conflict of interest

Authors have declared that no competing interests exist.

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